Optical and structural performance of the PolZero-Lm Time Domain Polarization Scrambler

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Abstract— **High precision reflectivity measurements by an orbiting spectrometric sensor (such as HyspIRI, ACE, and Geo-CAPE) require instrumental polarization sensitivity management. The most desirable method of management is total depolarization of the incoming signal with minimal adverse optical side effects. The PolZero design of time domain polarization scrambler has been able to achieve depolarization strength $0.80 \leq \Delta \leq 0.99$ across the spectral band 430-600 nm; in the symmetric spectral integration mode, the depolarization is $\Delta \geq 0.98$ across that band. In operation, the PolZero-Lm (ruggedized laboratory version) shows no apparent image duplication or deflection. This paper will present depolarization strength measurements, and polarized PSF measurements. Ruggedization of the photo-elastic modulator assemblies is critical to aircraft and satellite deployment of the PolZero in spectrometric or radiometric applications. We present initial results of vibration tests of the PolZero-Lm, showing robust performance in vibration-table and aircraft environments.**

Keywords-polarization; depolarizer; electro-optic; remote sensing

I. Introduction

Several NRC Decadal Survey (1) science objectives are based on spectrometric measurements over wide spectral ranges and large spatial extents. The upwelling Earth radiation is polarized, with the spatial and spectral polarization texture dependent on variations in the solar scattering geometry, the aerosol, cloud, and molecular content of the line of sight column, and the time dependence of multi-scale weather patterns. While this presents a rich harvest of information for a polarimetric sensor, it simultaneously produces a confounding overlay on the purely photometric assessment of spatio-spectral information, due to innate polarizance in spectrally diverse optical trains. Polarization management is a necessary part of spectrometric (and radiometric) sensors; without it, the few percent polarization differences from place to place can mask significant differences in ocean color and aerosol loading, for instance hiding toxic algal blooms harboring Vibrio cholerae, or obscuring rich fishing grounds

Mitigation of radiometric errors induced by variable polarization in the incident beam is accomplished by introducing a polarization control element early in the optical train; this element produces a known and controllable polarization state in the light seen by the downstream optics. Most often the controller element takes the form of a polarization scrambler that transforms its input into a quasi-unpolarized beam (see, *e.g.*, Collett (2)). The implementation of polarization scramblers can be difficult. Polarization scrambler designs fall into three major categories depending on the method of polarization averaging used: spatial, e.g. Babinet compensator devices; spectral, e.g. Lyot depolarizers; and temporal, PolZero using electro-optic polarization modulation.

The PolZero Time Domain Polarization Scrambler directly applies to instrument designs for several spectrometric missions recommended by the Decadal Survey. Independent measures of intensity with no polarization dependence using the ACE UV/Vis spectrometer are critical to separation of aerosol and ocean color contributions; the PolZero image quality, high depolarization, and wide angular acceptance angle will contribute to producing a compact and highly accurate spectrometer. Extraction of polarization-independent intensity over global fields of regard using GEO-CAPE requires compensation for significant polarization variations due to Rayleigh scattering geometry variations across the globe on the large scale, and to local variations in terrain reflectivity, water body color, and aerosol/cloud formations on the small scale. Sensor performance will benefit from PolZero's freedom from polarized beam separation effects, and its wide spectral applicability in a single optical unit. The ability to operate in a non-collimated optical space aids in designing a compact, optically efficient, instrument for geostationary orbit. Furthermore, the ability to use PolZero in both a scrambler and a polarimeter mode is ideally suited for a geostationary orbit.

PolZero can operate effectively in the spectral region 400-2500 nm due to its use of fused silica as the modulating element, enabling its use in GACM. An equivalent TDPS can be constructed for MWIR day-night CO measurements in the middle troposphere at 4.6 μm by replacing fused silica by zinc selenide. The need for a mid-IR depolarizer must be investigated in more depth since polarization phenomena in the MWIR are the sum of reflective and emissive phenomena; these orthogonal polarimetric contributions complicate MWIR polarization strength by producing both additive and subtractive effects. The net effect is often, but not always, a low degree of polarization.

For the HyspIRI hyperspectral sensor, the wide spectral and acceptance angle range of the PolZero permit polarization-

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independent spectral intensity imaging measurements with minimal optical interference – no additional collimated section is likely to be needed. The inherent non-birefringence of the PolZero modulator produces no depolarizer element beam splitting, permitting retention of optimal image quality.

Several versions of the PolZeroTime Domain Polarization Scrambler are in operation or planning. For the sake of clarity, we define the version with a postfix to the name. The versions are: PolZero-L, the original BATC laboratory version using stock Photo-Elastic Modulators (PEMs); PolZero-Lm, the version using stock PEMs modified for aircraft vibration survival (see Section IV); and PolZero-F1 is the first unified version for aircraft flight. If there is no postfix, in this paper, the default version is PolZero-Lm.

Section II outlines the method of operation of PolZero TDPS, and the measurement system used to quantify its performance. Section III presents current results for the PolZero-Lm laboratory unit spectral performance., while Section IV shows preliminary results of PolZero performance in realistic vibration test environments.

II. PolZero Operation

Spectrometers invariably have a significant response to different azimuths of polarized light. Aside from any polarizance of the beam-forming optical elements, reflection diffraction gratings will act as polarization analyzers. Both the bare reflective substrate and the grating lines have preferred directions, producing different reflectivities parallel and perpendicular to this direction. Mitigation of radiometric errors induced by variable polarization in the incident light is done by introducing a polarization control element early in the optical train; this element produces a known and controllable polarization in the light seen by the downstream optics. Most often the controller element takes the form of a polarization scrambler, which transforms its input into a quasi-unpolarized beam. The PolZero is a TDPS implemented as a pair of Photo-Elastic Modulators (PEMs) (3), set at an azimuthal angle to each other, operating as variable retarders. The retardance Δ of a PEM can be written as $\Delta(t) = A\sin(\omega t)$, where ω is the ~50 kHz acoustic frequency of operation; this ultrasonic frequency allows many depolarizer cycles during a typical integration time.

An ideal scrambler is represented by the ideal depolarizer Mueller matrix T_{scr}, which removes all polarization from the incoming beam while conserving the total intensity of the light passing through it,

$$\mathbf{T}_{scr}\mathbf{S}_{in} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \mathbf{T}_{scr}\left[\begin{pmatrix} S_0 - S_{pol} \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} S_{pol} \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \right] = \begin{pmatrix} S_0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

where $S_{pol} = \sqrt{S_1^{\,2} + S_2^{\,2} + S_3^{\,2}}$ is the polarized intensity. The degree to which T_{scr} has non-zero elements determines the degree to which the optical system transforms polarization variations into unwanted intensity variations.

The following optical setup, from optical entrance to exit, describes a PEM depolarizer:

1. Variable retarder #1 at angle $\theta_1 = \theta_{ref}$ with retardance Δ_1 at frequency ω_1
2. Variable retarder #2 at angle $\theta_2 = \theta_{ref} + \theta$ with retardance Δ_2 at frequency ω_2

Angle θ_i is the angle of the retarder fast axis relative to a reference direction θ_{ref}. we choose the reference direction to be horizontal, $\theta_{ref} = 0$, thereby defining the direction of Stokes parameter S_1. Angles of the optical axes are $\theta > 0$ for a counterclockwise rotation looking into the beam. Without loss of generality we set $\omega_2 = q\ \omega_1$.

The Mueller matrix **T** of the ideal optical system defined above is written as

$$\mathbf{T} = \mathbf{R}(\theta_2)\mathbf{Q}(\Delta_2)\mathbf{R}(-\theta_2)\mathbf{R}(\theta_1)\mathbf{Q}(\Delta_1)\mathbf{R}(-\theta_1)$$

where $Q(\Delta)$ is the Mueller matrix of a wave plate with retardance Δ and $R(\theta)$ is the rotation matrix for angle θ. Analysis of the $\mathbf{T}_{11}$ term requires θ to be $\pi/4$. Using the Bessel function approximation to the PEM retardance

$$\cos(A\sin\omega t) = J_0(A) + 2\sum_{k=1}^{\infty} J_{2k}(A)\cos(2k\omega t)$$

$$\sin(A\sin\omega t) = 2\sum_{k=0}^{\infty} J_{2k+1}(A)\sin\{(2k+1)\omega t\}$$

To zeroth order, after summing over is m >> 1 cycles of PEM oscillation, the TDPS Mueller matrix becomes

$$\langle \boldsymbol{T} \rangle = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & J_0(A_2) & 0 & 0 \\ 0 & 0 & J_0(A_1) & 0 \\ 0 & 0 & 0 & J_0(A_1)J_0(A_2) \end{pmatrix}$$

<T> becomes a very good approximation to the ideal depolarizer matrix if the retardance amplitudes are chosen to be $A_1 = A_2 = 2.405$ rad, the first zero of the J_0 Bessel function; see Illing (4) for more detail.

III. Spectral Bandpass Analysis

Because the retardance of a given length d of material (*e.g.* stressed fused silica) is $A = \beta d/\lambda$, with β the birefringence, the TDPS depolarization efficiency is wavelength dependent. We show below that the "usable" bandwidth of depolarization efficiency is quite wide, given a proper wavelength set point.

Fig. 1 shows the two modes of spectral integration possible

$$M_{ii} = \int_{z-\delta/2}^{z+\delta/2} J_0(z)\, dz$$

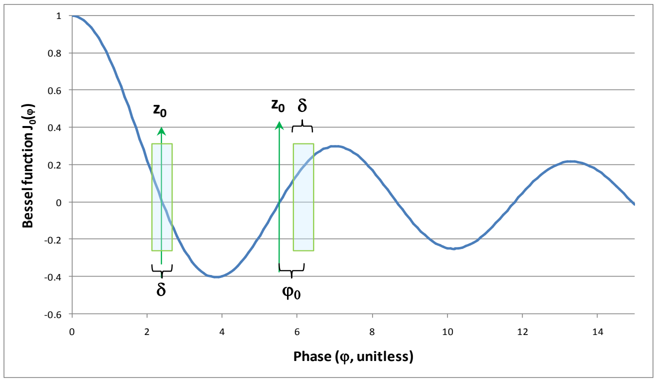


Figure 1: The two modes of spectral integration for the TDPS Mueller matrix elements. Left, symmetric mode, with the set point within the integration region. Right, Asymmetric mode, with the set point outside the integration region.

using the PolZero TDPS. Symmetric matrix element integration has the TDPS set point (*i.e.* the wavelength at which the J_0 phase is set to 2.405) within the integration region, equal to the operating wavelength or phase z:

This describes a bandpass (multispectral) filter, and generally gives small values for M_{ii} since the J_0 is fairly linear close to a

$$M_{ii} = \int_{z-\delta/2+\varphi_{off}}^{z+\delta/2+\varphi_{off}} J_0(z)\,dz$$

zero. Asymmetric mode has the set point outside the integration region, different from the operating wavelength:

This models the operation of a diffraction grating, and can produce larger M_{ii} values.

Measurements of the PolZero-Lm polarization scrambler were made at selected 10 nm wide wavelength bands from 450 nm to 630 nm using the Ball Mueller Matrix Imaging Polarimeter (4) (5). each measurement included the standard 3-step sequence of empty sample volume, PEMs off (PolZero inactive), and PEMs on (PolZero active),; this permits use of

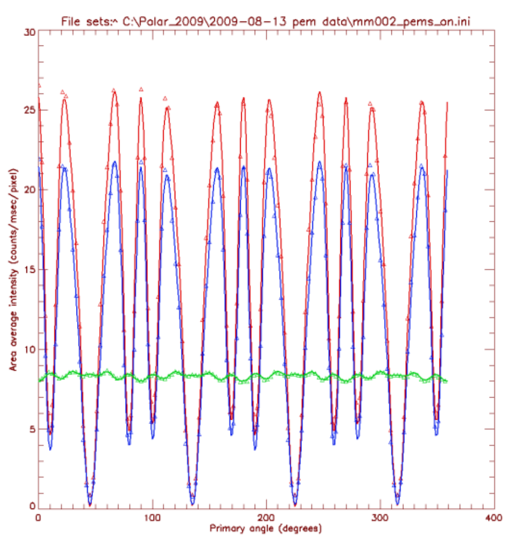


Figure 2: Intensity data from 3-step sequence of Mueller matrix measurement. Red, empty sample volume. Blue, PolZero in sample volume, inactive. Green, PolZero in sample volume, active.

Table 1: Mueller matrices for the example data shown in Fig. 2. POF: PolZero off; PON, PolZero on

POF 500		EC norm	
1.0000	-0.0520	0.0005	0.0090
-0.0454	1.0848	0.0125	0.0286
-0.0039	-0.0096	0.9070	0.0007
-0.0016	0.0039	-0.0012	1.0820
PON 500		**EC norm**	
1.0000	-0.0082	0.0012	0.0002
-0.0110	-0.0325	0.0000	-0.0027
0.0044	0.0027	-0.0540	-0.0028
0.0012	-0.0031	-0.0003	0.0061

the error compensation technique described in (6) (7) (8).

Fig. 2 shows the dramatic effect of the PolZero polarization scrambler. The red and blue lines show intensity data from the dual rotating Mueller matrix polarimeter with, respectively, the PolZero out of the beam, and in beam but inactive; the oscillatory signal amplitude is in this case indicative of the strength of polarization transmission through the optical element. When the PolZero is active, shown by the green line, the polarization transmission through the TDPS is very much reduced. Table 1 shows this quantitatively, as the measured Mueller matrices for PolZero off and on at a single wavelength band. Matrix POF-500 shows the result for PolZero inactive at 500 nm wavelength; Matrix PON-500 shows the strong reduction in the diagonal matrix elements that govern polarization transfer through the optical system. The small size of the off-diagonal elements reflects the noise level of the measurements.

$$\Delta_P = 1 - \frac{|M_{11}| + |M_{22}| + |M_{33}|}{3}$$

A similar Mueller matrix measurement was made at intervals through the range 450-630 nm. These data can be summarized by defining the depolarization power Δ_P of an optic describe by Mueller matrix M:

The Mueller matrix of an empty sample volume (or vacuum) is the unit matrix, so $\Delta_P = 0$, the vacuum has no depolarizing power. An ideal depolarizer, on the other hand (as in (1)), has $\Delta_P = 1$. Fig 3 shows the depolarization power of the PolZero-

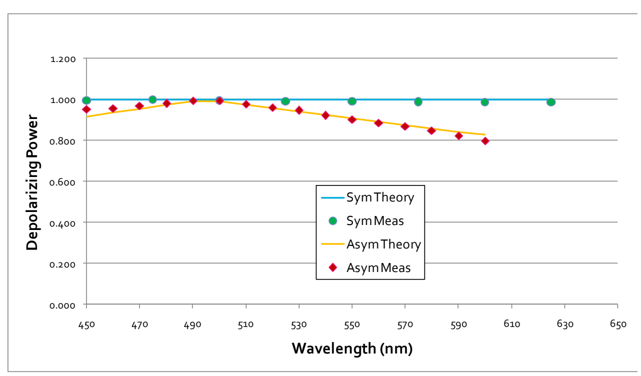


Figure 3: Depolarization power measured as a function of wavelength for both symmetric and asymmetric operation. Measurements are symbols, and theoretical values are lines.

Lm as a function of wavelength. For symmetric operation, set-point wavelength and phase equals operating wavelength and phase. For symmetric spectral intervals, the expected value of Δ_P is 1, and the measurements (green dots) fall on the theoretical line. For asymmetric operation, given set point wavelength λ_s and operating (measurement) wavelength λ_{op}, the operating phase point is $\varphi_{op} = 2.405\ \lambda_s / \lambda_{op}$; as wavelength increases from the set point, the absolute value of the J_0 increases, lowering the depolarization power.

The depolarization plot in Fig. 3 confirms the result seen from the Mueller matrix elements themselves. For symmetric operation over a spectral (filter) band, there is little variation expected with set point wavelength over the operational range of the PolZero, 0.3-2.5 μm. the asymmetric (grating) mode requires more specification for proper usage. Nevertheless, maintaining $\Delta_P > 0.9$ allows a spectral range of 100 nm or more. Since the behavior of the variation is known and well described, one may choose to make some correction ofr non-ideality and expand the acceptable spectral range to over 200 nm. Furthermore, it is likely that ongoing work will reduce the diagonal matrix elements of the PolZero-F1 even farther, enabling even wider spectral ranges to be used.

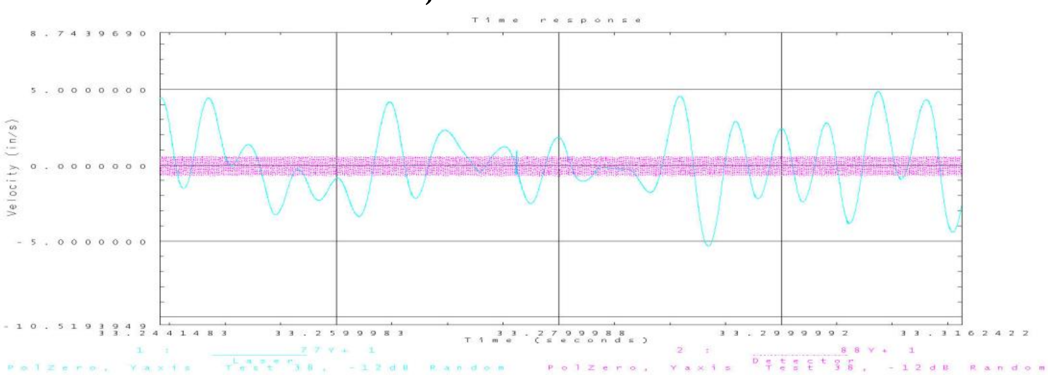
IV. VIBRATION TESTING

It is well known that the low power, high efficiency excitation scheme for operating PEMs (Hinds Instruments) can be somewhat mechanically delicate. Consequently, we verified operability for an aircraft flight opportunity in 2009 with a brief vibration test. The PolZero-L was found to need specific modification to reduce susceptibility to the Twin Otter vibration spectrum. This modification, done by Hinds Instruments, resulted in the PolZero-Lm; similar modifications had been made previously for a spaceflight sensor by JPL. The PolZero-Lm was vibration tested while installed in the BATC Polarization-neutralized Ocean/Littoral Color Assessment Sensor (POLCAS), the current version of which is more euphoniously called Glimmer.

A more specific set of vibration tests, of PolZero-Lm, has just been concluded; these tests include only the PolZero-Lm, with no additional sensor interference. The objectives of these tests are to verify the minimum operational envelope of the PolZero-Lm, to define, validate, and codify test procedures for the PolZero-F1 expected later this year, and to quantify the isolation of the photo-elastic modulators from vibrational cross-coupling due to the aircraft spectrum. The PEMs were active during this set of tests.

The maximum vibration level applied to the PolZero-Lm was the NASA Minimum workmanship Level, equivalent overall to 6.784 G (RMS). This slightly exceeds the assumed airborne platform, a DHC-6 Twin Otter. Tests were performed in all three axes, at -18 dB to -3 dB referred to 10 G (RMS).

a) 0.5 seconds duration



b) 0.05 seconds duration

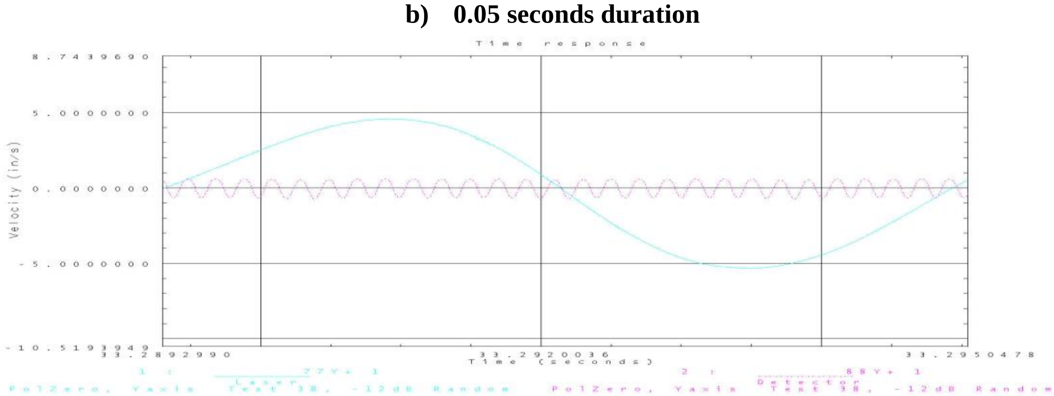


Figure 4: Preliminary data from the PolZero-Lm vibration test. Blue line, scale at left, shows the laser vibrometer data as proxy for applied force to the PEM optic. Red line, on arbitrary scale, shows the detected optical signal. Lower picture is blowup from upper data trace.

Vibrational cross-coupling was measured by passing a laser beam through the active pair of PEMs (tuned to $\lambda/4$ at 637.8 nm), producing a known and stable optical signal on a photodiode detector. A baseline signal was measured by the experimental setup on the vibration table before and after shaking. The modulated signal was easily seen and measured. Computerized signal acquisition at 100 kHz sample frequency easily resolved the mechanical modes from the very sharp PEM modes. Frequency scans covered the range 6-2000 Hz.

Figure 4 shows very interesting preliminary data. This test data was taken during a random vibration at amplitude -12 dB G (RMS) (ref 10 G) along the optical axis of the PolZero-Lm; this is the least constrained direction of motion due to the required mounting structure for the two PEMs. The blue line, with its scale at left, shows laser vibrometer data as a proxy for applied force to the PEM optic. The red line, with its scale at right, shows the detected optical signal through the two PEMs. Only one PEM was active, giving a sinusoidal signal at the detector. The lower panel is a blowup of a short section of the data shown in the upper panel. The applied vibration is clearly quite variable, but the envelope of PEM oscillation in the upper panel shows very little modulation at all, much less in phase with the applied force shown in blue. Expanding the scale to show individual PEM oscillations reinforces this observation; there appears to be little cross-coupling from the mechanical vibration into the optically active stress (acoustic) field. This conclusion appears to hold as well for the highest level of vibration tested. Detailed results will be reported in a future publication.

V. Summary

Spectral analysis of the PolZero-Lm shows that the depolarized bandwidth is suitable both for integrated spectral filters, using the center wavelength as the electronic set point (symmetric operation), and for spectrally resolved sensors (asymmetric operation). Asymmetric sensor acceptable bandwidth is a system design parameter; current capability gives at least 100 nm width, with reasonable expectation of wider bands as the technology matures.

Vibrational testing of the PolZero module by itself has been performed. Quick look data show the current Hinds Instrument vibration mitigation provides good isolation for aircraft vibration spectra, up to the NASA minimum workmanship level. Live measurement of PEM operation during vibration test shows stable signal levels and very low levels of mechanical-optical cross-coupling. Detailed analyses will be published in the near future.

Hinds Instruments is currently designing and fabricating the first unified PolZero unit, the PolZero-F1. This will have a unified opto-mechanical structure and an optimized, consolidated set of electronic controls. Delivery is expected in summer 2010.

Polarized point spread function tests are in progress, and will be published in the near future.

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